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SPECIFICATION

COMPUTER-GENERATED HOLOGRAM

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FIELD OF THE INVENTION

The present invention relates to a computer-generated hologram. In particular, the invention relates to a computer-generated holographic stereogram with high resolution and with many numbers of parallaxes.

10

BACKGROUND ART

A stereogram is known as a medium, which can be observed by an observer by changing over a plurality of images depending on the direction of observation. The stereogram widely used at present has a lens array such as lenticular lens, fly-eye lens, etc. arranged on a printing medium.

When this type of stereogram is used, by changing the direction of observation, a plurality of entirely different images can be changed over for observation of an observer. Also, when the stereogram is used, by changing the direction of observation, an image of a 3-dimensional object can be observed from a direction to match the direction of observation. In this case, the observer can observe the 3-dimensional object with stereoscopic effect. Further, when the stereogram is used, by changing the direction of observation, a plurality of images gradually changing can be observed by an observer. In this case, the

observer can observe the plurality of changing images as a series of animated images. The display of the changeover of a plurality of images, the display of images with stereoscopic effect, and the display of images with animation effect as described above can be combined together and used at the same time.

In addition to the stereogram, in the Patent Reference 1, a screen is proposed, which comprises a group of pixels, and each pixel is divided to a plurality of regions. Then, different diffraction grating is assigned to each region so that, when it is seen from different directions, different images can be observed as an assembly of diffraction grating regions to project diffracted light in the direction.

[Patent Reference]

Japanese Patent Publication No. 2795698

[Patent Reference 2]

JP-A-2002-72837

[Non-Patent Reference 1]

Junpei Tsujiuchi: "Physics Selection 22; Holography", pp.33-36 (published by Shokabo Co., Ltd.; November 5, 1997).

The stereogram comprising a printed matter with a lens array such as lenticular lens, fly-eye lens, etc. as described above requires physical pixel structure (lens array). Thus, it is disadvantageous in that the product has low resolution and is too thick. Also, it requires fine and minute printing and the printing area is limited.

In this respect, it is not possible to attain the following two purposes: the improvement of resolution and the increase of number of parallaxes.

According to the patent reference 1, pixels in limited size are cut in each direction of parallax and diffraction grating is assigned and used. This also requires a limited area, and it is not possible to attain the two purposes as given above: the improvement of resolution and the increase of number of parallaxes.

To solve the problems of the prior art as described above, it is an object of the present invention to provide a computer-generated holographic stereogram, which has very high resolution and many numbers of parallaxes.

DISCLOSURE OF THE INVENTION

To overcome the disadvantages of the prior art as described above, a first computer-generated hologram according to the present invention is a computer-generated hologram for selectively reproducing a plurality of images depending on the direction of observation where complex amplitude of an object wave is recorded, wherein:

a virtual point light source group is set up spatially on a side opposite to the observation side of the hologram, luminance angular distribution $A_{WLci}(\theta_{xx}, \theta_{yz})$ of divergent light diverged from each of the virtual point light sources of said virtual point light source group toward observation side is divided by angular division, and within the divided angle, among the multiple images positioned on the plane of

said virtual point light source group, a divergent light diverged from a point of amplitude equal to the density of pixel of the image corresponding to each of divided angle or equal to a value in a certain fixed relation with the
5 density of the images at the position of the virtual point light source is recorded as the object light at one of the positions on the observation side of the virtual point light source group.

In this case, each of the virtual point light sources
10 in the virtual point light source group is a point light source where the spreading direction of the light is mono-dimensional, and it may comprise a linear light source, which extends in a direction perpendicularly crossing the spreading direction.

15 A second computer-generated hologram of the present invention is a computer-generated hologram for selectively reproducing a plurality of images depending on the direction of observation where complex amplitude of an object wave is recorded, wherein:

20 when a predetermined illuminating light enters, a diffracted light is reconstructed, which advances as it is diverged toward observation side from each of the points of spatial virtual point group on a side opposite to observation side of the hologram, luminance angular
25 distribution of the light is divided by angular division depending on the direction of diffraction angle so that the light is diverged from each virtual point toward the observation side of the hologram, and the diffracted light

is equal to the divergent light diverging from a point with an amplitude equal to the density of pixel of the image corresponding to each divided angle or equal to a value in a certain fixed relation with the density at the position
5 of the virtual point of the recorded images among the separate recorded images positioned on the plane of said virtual point group within the divided angle.

In this case, each of the virtual points of the virtual point group is a point where the spreading
10 direction of the light is mono-dimensional, and it may comprises a straight line extending in a direction perpendicularly crossing the spreading direction.

A third computer-generated hologram of the present invention is a computer-generated hologram for selectively
15 reproducing a plurality of images depending on the direction of observation where complex amplitude of an object wave is recorded, wherein:

a virtual light converging point group is spatially set up on observation side of the hologram, luminance
20 angular distribution $T_{WLCi} (\theta_{xz}, \theta_{yz})$ of converged light entering from the side opposite to the observation side to each of the virtual light converging points of said virtual light converging point group is divided by angular division, and within the divided angle, among the multiple images
25 positioned on the plane of said virtual light converging point group, these converging lights are converged to a point of amplitude equal to the density of pixel of the image corresponding to each of the divided angle or equal

to a value in a certain fixed relation with the density of the images at the position of the virtual light converging point, and the converging lights are recorded as the object light at one of the positions on a side opposite to the
5 observation side of the virtual light converging point group.

In this case, each of virtual light converging points of the virtual light converging point group is a light converging point where the spreading direction of the light
10 is mono-dimensional, and it may comprise a linear light converging light extending in a direction perpendicularly crossing the spreading direction.

A fourth computer-generated hologram of the present invention is a computer-generated hologram for selectively
15 reproducing a plurality of images depending on the direction of observation where complex amplitude of an object wave is recorded, wherein:

when a predetermined illuminating light enters, a diffracted light is reconstructed, which is diverged at
20 observation side through each point of spatial virtual point group on the observation side of the hologram, luminance angular distribution of the light converged to each virtual point is divided by angular division depending on the direction of diffraction angle, and among the
25 separate recorded images positioned on the plane of said virtual point group within each of the divided angles, these converging lights are the diffracted lights converged to a position of amplitude equal to the density of pixel of

the image corresponding to each divided angle or equal to a value in a certain fixed relation with the density at the position of virtual point of the recorded images, and the converged lights are reconstructed in this manner.

5 In this case, each of the virtual points of the virtual point group is a point where spreading direction of the light is mono-dimensional, and it may comprise a straight line extending in a direction perpendicularly crossing the spreading direction.

10 In the present invention, on a plane where a plurality of images such as parallax images are reconstructed and which is separated from the plane of the hologram, a multiple of virtual point light sources with luminance equal to the luminance of the position of the images
15 different depending on radiating direction or a multiple of virtual light converging points with luminance equal to the luminance of the directions of the images different depending on light converging direction are defined. Light components radiated from these virtual point light sources
20 or light components converged to these virtual light converging points are regarded as virtual object light, and a computer-generated hologram is prepared by using these light components. As a result, a computer-generated hologram can be prepared by using a light radiated from
25 these virtual point light sources or a light converged to these virtual light converging points. Thus, it is possible to obtain a computer-generated hologram, which has high resolution and can record and reconstruct a multiple

of images and which does not require hologram photographing. The present invention provides, for instance, a computer-generated holographic stereogram, which has high resolution and has many numbers of parallaxes.

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BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a drawing to explain a principle of a computer-generated hologram according to the present invention;

10 Fig. 2 is a drawing to explain how an observer can selectively observe different images depending on the direction of parallax through the computer-generated hologram as shown in Fig. 1;

Fig. 3 is a flow chart to explain a method for
15 preparing the computer-generated hologram as shown in Fig. 1;

Fig. 4 is a drawing to explain another embodiment of the computer-generated hologram of the present invention;

Fig. 5 is a drawing to explain how an observer can
20 selectively observe different images depending on the direction of parallax through the computer-generated hologram as shown in Fig. 4; and

Fig. 6 is a flow chart to explain a method for
preparing the computer-generated hologram as shown in Fig.
25 4.

BEST MODE FOR CARRYING OUT THE INVENTION

The basic principle of a computer-generated hologram

according to the present invention is as follows:

On a plane where a plurality of images such as parallax images is reconstructed and which is separated from the plane of the hologram, a multiple of virtual point
5 light sources with luminance of the positions of the images different depending on radial direction or a multiple of virtual light converging points with luminance equal to the luminance of the positions of the images different
depending on light converging direction are defined. Light
10 components radiated from these virtual point light sources or light components converged to these virtual light converging points are regarded as virtual object light, and a computer-generated hologram is prepared using these light components. As a result, images with high resolution and
15 with many numbers of parallaxes can be recorded. Thus, a computer-generated hologram (CGH) is prepared, which requires no hologram photographing.

Description will be given below on general principle of the computer-generated hologram according to the present
20 invention.

As shown in Fig. 1, which represents the basic principle, a virtual point light source group 11, a CGH 12, and observers M are provided in (+) direction along z-axis in this order. The center of the CGH 12 is regarded as the
25 origin of coordinates, and x-axis and y-axis cross each other perpendicularly. These axes also cross z-axis perpendicularly. It is supposed that the coordinates of the virtual point light source group 11 are (x_1, y_1, z_1) ,

and the coordinates of the CGH 12 are (x_2, y_2, z_2) . Then, i -th virtual point light source is defined as $Q_i (x_1, y_1, z_1)$ and j -th cell of CGH 12 is defined as $P_j (x_2, y_2, z_2)$. It is assumed that a view point of an observer M is on an extension of a straight line $Q_i P_j$. The luminance with wavelength λ_c in the directions θ_{xz} and θ_{yz} at the virtual point light source $Q_i (x_1, y_1, z_1)$, observable from the view point of the observer M, is defined as $A_{WLCi} (\theta_{xz}, \theta_{yz})$. Here, θ_{xz} is an angle with respect to z -axis when the straight line $Q_i P_j$ is incident to the plane x - z , and θ_{yz} is an angle with respect to z -axis when the straight line $Q_i P_j$ is incident to the plane y - z .

It is supposed now that initial phase of the virtual point light source Q_i is ϕ_{WLCi} , and a distance between Q_i and P_j is r_{ij} . Then, a complex amplitude value $O_{WLC} (x_2, y_2, z_2)$ is given as:

$$O_{WLC} (x_2, y_2, z_2) = \sum_{i=1}^N \{A_{WLCi} (\theta_{xz}, \theta_{yz}) / |r_{ij}|\} \times \exp [j \{(2\pi/\lambda_c) r_{ij} + \phi_{WLCi}\}] \quad \dots\dots (1)$$

where N represents the number of Q_i .

A luminance $A_{WLCi} (\theta_{xz}, \theta_{yz})$ from the virtual point light source $Q_i (x_1, y_1, z_1)$ is divided by angular division with respect to θ_{xz} and θ_{yz} . In each of the divided angles, the density of pixel of the image of the image corresponding to the divided angle at the position of the virtual point light source $Q_i (x_1, y_1, z_1)$ of the image is assigned. For instance, the angle θ_{xz} is divided to $\theta_{xz0} \sim \theta_{xz1} \sim \theta_{xz2} \sim \dots\dots \sim \theta_{xzm}$ within angle range of $-\pi/2$ to

$\pi/2$, and the angle θ_{yz} is divided to $\theta_{yz0} \sim \theta_{yz1} \sim \theta_{yz2}$
 $\sim \dots \sim \theta_{yzn}$ within angle range of $-\pi/2$ to $\pi/2$ to have
 equal angular distance. Then, the density I_{111} at the
 position of the virtual point light source Q_1 of the image
 5 I_{11} is assigned to the range of $\theta_{xz0} \sim \theta_{xz1}$ and to the range
 of $\theta_{yz0} \sim \theta_{yz1}$. The density I_{211} at a position of the
 virtual point light source Q_i of the image I_{21} is assigned
 to the range of $\theta_{xz1} \sim \theta_{xz2}$ and $\theta_{yz1} \sim \theta_{yz1}$. The density I_{mni}
 at a position of the virtual point light source Q_i of the
 10 image I_{mn} is assigned to the range of $\theta_{xzm-1} \sim \theta_{xzm}$ and θ_{yzn-1}
 $\sim \theta_{yzn}$.

Explaining in simpler manner, in Fig. 1, the object
 wave 1 emitted in the direction of parallax 1 from the
 virtual point light source $Q_1 (x_1, y_1, z_1)$ is turned to a
 15 wave, which has the density at pixel position i of a first
 image I_1 (e.g. a letter "A") as the amplitude of the
 virtual point light source. The object wave 1 emitted in
 the direction of parallax 2 is turned to a wave, which has
 the density at pixel position i of a second image I_2 (e.g.
 20 the letter "B") as the amplitude of the virtual point light
 source. Similarly, the object wave 1 emitted in the
 direction of parallax 8 is turned to a wave, which has the
 density at pixel position i of an 8th image I_8 (e.g. a
 letter "H") as the amplitude of the virtual point light
 25 source. Then, the object wave 1 is generated, which has
 the density at pixel position i of the letters "A",
 "B", "H" corresponding to parallax direction as
 amplitude at the same time. This object wave 1 is given by

the equation (1).

Here, the density is supposed to be a value, which takes a bigger value when brightness is high as generally used in digital image. (It is considered that, when black and white are compared with each other, white has higher density.)

Here, it is supposed that incident vector of a reference light 2, which consists of parallel lights entering the CGH 12 is (R_x, R_y, R_z) , and that the amplitude of the wavelength λ_c is R_{WLC0} . Also, it is supposed that the phase at the origin of coordinates is ϕ_{RWLC} . Then, complex amplitude value $R_{WLC}(x_2, y_2, z_2)$ is given as:

$$R_{WLC}(x_2, y_2, z_2) = R_{WLC0} \cdot \exp [j \{ (2\pi/\lambda_c) \times (R_x x_2 + R_y y_2 + R_z z_2) / (R_x^2 + R_y^2 + R_z^2)^{1/2} + \phi_{RWLC} \}] \quad \text{..... (2)}$$

The intensity $I_{WLC}(x_2, y_2, z_2)$ of interference fringes caused by the object wave 1 at $P_j(x_2, y_2, z_2)$ and the reference light 2 are given by:

$$I_{WLC}(x_2, y_2, z_2) = |O_{WLC}(x_2, y_2, z_2) + R_{WLC}(x_2, y_2, z_2)|^2 \quad \text{..... (3)}$$

In the above, a distance r_{1j} between Q_i and P_j is given as:

$$r_{1j} = \{ (x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2 \}^{1/2} \quad \text{..... (4)}$$

An angle θ_{xz} with respect to z-axis when the straight line $Q_i P_j$ is incident to the plane x-z is given as:

$$\theta_{xz} = \tan^{-1} \{ (x_2 - x_1) / (z_2 - z_1) \} \quad \text{..... (5)}$$

An angle θ_{yz} with respect to z-axis when the straight line $Q_i P_j$ is incident to the plane y-z is given as:

$$\theta_{yz} = \tan^{-1} \{ (y_2 - y_1) / (z_2 - z_1) \} \quad \dots\dots (6)$$

Initial phase ϕ_{WLCi} of the virtual point light source Q_i is set to a fixed value between the virtual point light sources Q_i regardless of the relation of the virtual point
 5 light sources to each other.

As it is evident from the above description, a multiple of virtual point light sources Q_i (x_i, y_i, z_i) are set up on planes of a plurality of images $I_{11}, I_{21}, \dots\dots, I_{mn}$, which can be recorded and reconstructed on the same
 10 plane as the CGH 12. Luminance angular distribution A_{WLCi} (θ_{xz}, θ_{yz}) of divergent light radiated from each of the virtual point light sources Q_i is divided depending on the direction of the radiant angle. Within different divided angle, luminance is set to a value equal to the density $I_{111},$
 15 $I_{211}, \dots\dots, I_{mn1}$ at the position of the virtual point light source Q_i of different images $I_{11}, I_{21}, \dots\dots, I_{mn}$. The initial phase ϕ_{WLCi} of the virtual point light source Q_i is set to a constant value between the virtual point light sources Q_i regardless of the relation to each other. Then,
 20 the phase and the amplitude of the divergent light from the virtual point light source Q_i are holographically recorded (recording of interference with the reference light 2). As a result, by the CGH 12 of the present invention, images $I_{11}, I_{21}, \dots\dots, I_{mn}$ different depending on the direction of
 25 observation can be obtained.

When an illuminating light 15 with the same wavelength λ_c as the reference light 2 is incident at the same incident angle as that of the reference light 2 to the CGH

12 as shown in Fig. 2, the images $I_{11}, I_{21}, \dots, I_{mn}$ are reconstructed on the plane of the virtual point light source group 11 as virtual images by a diffracted light 16 diffracted from the CGH 12. However, the diffracted light 5 16 relating to the images $I_{11}, I_{21}, \dots, I_{mn}$ is divided in angle depending on the direction of diffraction angle. From the position of the virtual point light sources $Q_1 (x_1, y_1, z_1)$ on the planes of the virtual point light source group 11, the diffracted light 16 to reconstruct the image 10 I_{11} is diffracted in the range of $\theta_{xz0} \sim \theta_{xz1}$ and $\theta_{yz0} \sim \theta_{yz1}$. The diffracted light 16 to reconstruct the image I_{21} is diffracted in the range of $\theta_{xz1} \sim \theta_{xz2}$ and $\theta_{yz0} \sim \theta_{yz1}$. The diffracted light to reconstruct the image I_{mn} is diffracted in the range of $\theta_{xzm-1} \sim \theta_{xzm}$ and $\theta_{yzn-1} \sim \theta_{yzn}$.

15 Explaining in simpler manner by referring to Fig. 2, by the diffracted light 16 emitted in the direction of parallax 1 from the virtual point light source $Q_1 (x_1, y_1, z_1)$, it is turned to a wave, which has the density of pixel at a position of the virtual point light source $Q_1 (x_1, y_1, z_1)$ of a first image I_1 (e.g. the letter "A") as amplitude. 20 By the diffracted light 16 emitted in the direction of parallax 2, it is turned to a wave, which has the density of pixel at a position of the virtual point light source $Q_1 (x_1, y_1, z_1)$ of a second image I_2 (e.g. the letter "B") as 25 amplitude. Similarly, the object wave 1 emitted in the direction of parallax 8 is turned to a wave, which has the density of pixel at a position of the virtual point light source $Q_1 (x_1, y_1, z_1)$ of an eighth image I_8 (e.g. the

letter "H") as amplitude. When the observer M observes CGH 12 from a parallax direction, these images "A", "B",, "H" can be selectively observed as an assembly of all pixels on the planes of the virtual point light sources, depending on the direction of parallax. Also, when the observer shifts the view point, these images "A", "B",, "H" can be observed as if these are changed over with each other.

Next, description will be given on a method to prepare the CGH 12 as described above as a binary hologram by referring to Fig. 3. In Step ST1, a plurality of images I_{11} , I_{21} ,, I_{m1} are defined. Next, in Step ST2, spatial arrangement of the virtual point light source group 11, the CGH 12 and the reference light 2 as well as a sampling point (Q_1) of the virtual point light source group 11 and a sampling point (P_j) of the CGH 12 are defined. Next, in Step ST3, luminance angular distribution $A_{WLCi}(\theta_{xz}, \theta_{yz})$ is divided by angular division depending on the direction of radiant angle. Then, the luminance of the different images I_{11} , I_{21} ,, I_{m1} within the divided angle is obtained as a luminance equal to the density I_{111} , I_{211} ,, I_{m11} at the position of the virtual point light source Q_1 . In Step ST4, a complex amplitude value $O_{WLC}(x_2, y_2, z_2)$ of the object light on the plane of the CGH 12 and a complex amplitude value $R_{WLC}(x_2, y_2, z_2)$ of the reference light 2 are calculated according to the equations (1) and (2). Then, in Step ST5, intensity of interference fringes of the object light and the reference light is obtained at each of

the sampling points defined on the plane of the CGH 12 according to the equation (3), and the data of the interference fringes are obtained. Next, in Step ST6, the data of interference fringes thus obtained are quantized.

5 In Step ST7, the data are converted to rectangular data for EB lithography. In Step ST8, the data are recorded on a medium by EB lithography device and the CGH 12 is obtained.

In the case shown in Fig. 1, it is designed that the object wave from the virtual point light source Q_1 enters
10 all cells P_j of the CGH 12 in x direction and y direction. However, it may be designed in such manner that the virtual point light source group 11 and the CGH 12 are divided by a multiple of slicing planes perpendicular to y-axis, and radiation range of the object wave may be limited within
15 the slicing planes.

Also, a point light source within 2-dimensional plane is used as the virtual point light source, while it may be designed in such manner that a linear light source extending in y direction and not spreading in y direction
20 may be used.

Further, in the case shown in Fig. 1, the method based on the interference with the reference light 2 is used for the purpose of fixing the complex amplitude value $Q_{WLC}(x_2, y_2, z_2)$ of the object light (object wave) 1 as hologram,
25 while the method of Lohmann or the method of Lee (non-patent reference 1) to directly reconstruct complex amplitude of the object wave may be used. Also, the method proposed by the present inventor in the patent reference 2

may be used. In the explanation for Fig. 1, the value of the image to match the luminance angular distribution $A_{WLCi}(\theta_{xz}, \theta_{yz})$ of the divergent light emitted from each of the virtual point light sources Q_i is used as the density of the pixel at the position of the virtual point light source Q_i . However, it is not limited to this, and a value in a certain relation with the density of the pixel may be used. For instance, by supposing that the density is X , a value \sqrt{X} , $X^{1/a}$ may be used (where "a" is a constant).

Fig. 4 is a drawing to explain another embodiment of the computer-generated hologram according to the present invention. In this embodiment, the virtual point light source group 11 in Fig. 1 is replaced with the CGH 12, and the virtual point light source group 11 is replaced by the virtual light converging point group 13. As shown in Fig. 4, the CGH 12, the virtual light converging point group 13, and the observers M are arranged in (+) direction along z-axis in this order. The center of the CGH 12 is regarded as the origin of the coordinates. It is defined that x-axis and y-axis run perpendicularly to each other, and that these are running perpendicularly to z-axis. The coordinates of the virtual light converging point group 13 are set to (x_1, y_1, z_1) and the coordinates of the CGH 12 are set to (x_2, y_2, z_2) . The i-th virtual light converging point is set to $Q_i (x_1, y_1, z_1)$ (using the same symbol as in the virtual light converging point sources), and the j-th cell of the CGH 12 is defined as $P_j (x_2, y_2, z_2)$. It is supposed that the view point of the observer M is on an

extension of the straight line $Q_i P_j$, and that the luminance at wavelength λ_c in the direction θ_{xz} and θ_{yz} at the virtual light converging point $Q_i (x_1, y_1, z_1)$ is $T_{WLCi} (\theta_{xz}, \theta_{yz})$. Here, θ_{xz} is an angle with respect to z-axis when the straight line $Q_i P_j$ is incident to the plane x-z, and θ_{yz} is an angle with respect to z-axis when the straight line $Q_i P_j$ is incident to the plane y-z.

It is supposed here that the initial phase of the virtual light converging point Q_i is ϕ_{WLCi} , and a distance between Q_i and P_j is r_{ij} . Then, a complex amplitude value $O_{WLC} (x_2, y_2, z_2)$ of the object wave entering $P_j (x_2, y_2, z_2)$ is as given below, instead of the above equation (1):

$$O_{WLC} (x_2, y_2, z_2) = \sum_{i=1}^N \{ T_{WLCi} (\theta_{xz}, \theta_{yz}) / |r_{ij}| \} \times \exp [j \{ - (2\pi/\lambda_c) |r_{ij}| + \phi_{WLCi} \}] \dots (1')$$

where N represents the number of Q_i .

Radiant luminance $T_{WLCi} (\theta_{xz}, \theta_{yz})$ emitted toward the observer from the virtual light converging point $Q_i (x_1, y_1, z_1)$ is divided by angular division with respect to θ_{xz} and θ_{yz} . Then, the density of pixel is assigned at a position of the virtual light converging point of an image corresponding to each dividing angle for each image within the divided angle. For example, the angle θ_{xz} is divided to $\theta_{xz0} \sim \theta_{xz1} \sim \theta_{xz2} \sim \dots \theta_{xzn}$ within the angle range of $-\pi/2$ to $\pi/2$. The angle θ_{yz} is divided to $\theta_{yz0} \sim \theta_{yz1} \sim \theta_{yz2} \sim \dots \theta_{yzn}$ within angle range of $-\pi/2$ to $\pi/2$ with equal angular spacing between them. The density I_{111} at the

position of the virtual light converging point Q_i of the image I_{11} is assigned to the ranges of $\theta_{xz0} \sim \theta_{xz1}$ and $\theta_{yz0} \sim \theta_{yz1}$. The density I_{21i} at the position of the virtual light converging point Q_i of the image I_{21} is assigned to the ranges of $\theta_{xz1} \sim \theta_{xz2}$ and $\theta_{yz0} \sim \theta_{yz1}$. The density I_{mni} at the position of the virtual light converging point Q_i of the image I_{mn} is assigned to the ranges of $\theta_{xzB-1} \sim \theta_{xzB}$ and $\theta_{yzB-1} \sim \theta_{yzB}$ as luminance within the divided angle.

Explaining in simpler manner, in Fig. 4, the object wave 1 emitted in the direction of parallax 1 after converging to the virtual light converging point $Q_i (x_1, y_1, z_1)$ is turned to a wave, which has the density at the pixel position i of a first image I_1 (e.g. the letter "A") as amplitude. The object wave issued to the direction of parallax 2 is turned to a wave, which has the density at pixel position i of a second image I_2 (e.g. the letter "B") as amplitude. Similarly, the object wave 1 emitted in the direction of parallax 8 is turned to a wave, which has the density at pixel position i of an eighth image I_8 (e.g. the letter "H") as amplitude.

An object wave 1 is generated, which has the densities at the pixel position i of the letters "A", "B", "H" at the same time depending on the direction of parallax. The object wave 1 is as given in the equation (1').

Here, it is supposed that incident vector of the reference light 2, which consists of parallel lights entering the CGH 12, is (R_x, R_y, R_z) , that the amplitude of the wavelength λ_c is R_{WLc0} , and that the phase at the origin

of the coordinates is ϕ_{RWLC} . Then, the complex amplitude value $R_{WLC}(x_2, y_2, z_2)$ of the reference light 2 is given, as in the case of Fig. 1, as follows:

$$R_{WLC}(x_2, y_2, z_2) = R_{WLC0} \cdot \exp [j \{ (2\pi/\lambda_c) \times (R_x x_2 + R_y y_2 + R_z z_2) / (R_x^2 + R_y^2 + R_z^2)^{1/2} + \phi_{RWLC} \}] \quad \text{..... (2)}$$

The intensity value $I_{WLC}(x_2, y_2, z_2)$ of interference fringes caused by the object wave 1 and the reference light 2 at $P_j(x_2, y_2, z_2)$ is given similarly as:

$$1) \quad I_{WLC}(x_2, y_2, z_2) = |O_{WLC}(x_2, y_2, z_2) + R_{WLC}(x_2, y_2, z_2)|^2 \quad \text{..... (3)}$$

In the above, the distance r_{1j} between Q_1 and P_j is given as:

$$r_{1j} = \{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2\}^{1/2} \quad \text{..... (4)}$$

15 The angle θ_{xz} with respect to z-axis when the straight line Q_1P_j is incident to the plane x-z is:

$$\theta_{xz} = \tan^{-1} \{(x_2 - x_1) / (z_2 - z_1)\} \quad \text{..... (5)}$$

The angle θ_{yz} with respect to z-axis when the straight line Q_1P_j is incident to the plane y-z is given as:

$$20 \quad \theta_{yz} = \tan^{-1} \{(y_2 - y_1) / (z_2 - z_1)\} \quad \text{..... (6)}$$

The phase ϕ_{WLC1} at the virtual light converging point Q_1 is set to a constant value between the virtual light converging points Q_i regardless of the relation to each other.

25 As it is evident from the above description, a multiple of the virtual light converging points $Q_i(x_1, y_1, z_1)$ are set up on planes of a plurality of images $I_{11}, I_{21}, \dots, I_{mn}$ recordable and reproducible on the same

plane as the CGH 12. Luminance angular distribution T_{WLCi}
 $(\theta_{xz}, \theta_{yz})$ of convergent light entering each of the virtual
light converging points Q_i is divided by angular division
depending on the direction of radiant angle. Within
5 different divided angle, luminance equal to the density I_{11i} ,
 I_{21i} ,, I_{mni} at the position of the virtual light
converging point Q_i of different images I_{11} , I_{21} ,, I_{mn}
is set up, and initial phase ϕ_{WLCi} of the virtual light
converging point Q_i is set to a constant value between the
10 virtual light converging points Q_i regardless of the
relation to each other. The phase and the amplitude of the
converging light entering the virtual light converging
points Q_i are recorded holographically (recording of
interference with the reference 2), and the CGH 12 of the
15 present invention can be obtained, in which the different
images I_{11} , I_{21} ,, I_{mn} can be reconstructed depending
on the direction of observation.

When it is designed in such manner that an
illuminating light with the same wavelength λ_c as the
20 reference light 2 enters the CGH 12 recorded at the same
incident angle as the reference light 2 as shown in Fig. 5,
the images I_{11} , I_{21} ,, I_{mn} are reconstructed as
superimposed on each other on the planes of the virtual
light converging point group 13 by the diffracted light 16
25 diffracted from the CGH 12. However, the diffracted light
16 relating to each of the images I_{11} , I_{21} ,, I_{mn} is
divided by angular division depending on the direction of
diffraction angle. From the position of the virtual light

converging point $Q_i (x_1, y_1, z_1)$ on the planes of the virtual light converging point group 13, the diffracted light 16 to reconstruct the image I_{11} is diffracted in the ranges of $\theta_{xz0} \sim \theta_{xz1}$ and $\theta_{yz0} \sim \theta_{yz1}$. The diffracted
 5 light 16 to reconstruct the image I_{21} is diffracted in the range of $\theta_{xz1} \sim \theta_{xz2}$ and $\theta_{yz0} \sim \theta_{yz1}$, and diffracted light 16 to reconstruct the image I_{mn} is diffracted in the ranges of $\theta_{xzm-1} \sim \theta_{xzm}$ and $\theta_{yzn-1} \sim \theta_{yzn}$.

Explaining in simpler manner by referring to Fig. 5,
 10 by the diffracted light 16 emitted in the direction of parallax 1 from the virtual light converging point $Q_i (x_1, y_1, z_1)$, it is turned to a wave, which has the density of pixel at the position of the virtual light converging point $Q_i (x_1, y_1, z_1)$ of a first image I_1 (e.g. the letter "A") as
 15 amplitude. By the diffracted light 16 emitted in the direction of parallax 2, it is turned to a wave, which has the density of pixel at the position of the virtual light converging point $Q_i (x_1, y_1, z_1)$ of a second image I_2 (e.g. the "B") as amplitude. Similarly, the object wave 1
 20 emitted in the direction of parallax 8 is turned to a wave, which has the density of pixel at the position of the virtual light converging point $Q_i (x_1, y_1, z_1)$ of an eighth image I_8 (e.g. the letter "H") as amplitude. When the observer M observes the direction of parallax, these images
 25 "A", "B",, "H" can be selectively observed depending on the direction of parallax as an assembly of all pixels on the planes of the virtual light converging point group 13. Also, when the observer shifts the view point, these

images "A", "B", , "H" can be observed as if these are changed over with each other.

Next, description will be given on a method to prepare the CGH 12 as a binary hologram by referring to Fig. 6. In

5 Step ST1, a plurality of the images I_{11i} , I_{21i} , , I_{mni} to be turned to the CGH are defined. Next, in Step ST2, spatial arrangement of the CGH 12, the virtual light converging point group 13, and the reference light 2 as well as a sampling point (Q_i) of the virtual light

10 converging point group 13 and a sampling point (P_j) of the CGH 12 are defined. Then, in Step ST3, luminance angular distribution T_{WLCi} (θ_{xz} , θ_{yz}) is divided by angular division depending on the direction of radiant angle for each virtual light converging point, and it is obtained as the

15 luminance equal to the densities I_{11i} , I_{21i} , , I_{mni} at the position of the virtual light converging point Q_i of the different images I_{11} , I_{21} , , I_{mn} within different divided angle. Then, in Step ST4, the complex amplitude value O_{WLC} (x_2 , y_2 , z_2) of the object light on the plane of

20 the CGH 12 and the complex amplitude value R_{WLC} (x_2 , y_2 , z_2) of the reference light 2 are calculated by using the equations (1') and (2). Then, in Step ST5, the intensity of interference fringes of the object light and the reference light can be obtained at each of the sampling

25 points defined on the plane of the CGH 12 by using the equation (3). Next, in Step ST6, the data of interference fringes thus obtained are quantized. In Step ST7, the data are converted to rectangular data for EB lithography. In

Step ST8, the data are recorded on a medium by EB lithography device, and the CGH 12 can be obtained.

In the case shown in Fig. 4, it is designed in such manner that the object wave entering the virtual light
5 converging point Q_i enters all of the cells P_j of the CGH 12 in x direction and y direction. However, it may be designed in such manner that the virtual light converging point group 13 and the CGH 12 are cut by a multiple of slicing planes perpendicular to y-axis, and radiation range
10 of the object wave is limited within the slicing planes.

Also, in Fig. 4, the light converging points within 2-dimensional plane are used as the virtual light converging points, while a light converging line extending in y direction and not spreading in y direction may be used.

15 Further, in the case of Fig. 4, a procedure based on the interference with the reference light 2 is adopted for the purpose of fixing the complex amplitude value Q_{WLG} (x_2 , y_2 , z_2) of the object light 1 as hologram, while the method of Lohmann or the method of Lee (non-patent reference 1) to
20 directly reconstruct the complex amplitude of the object wave may be used. Also, the method proposed by the present inventor in the patent reference 2 may be used.

Further, in the description given for Fig. 4, the density of pixel at the position of the virtual light
25 converging point Q_i is used as the value of the image corresponding to the luminance angular distribution T_{WLCi} of the converging light to be converged to each of the virtual light converging points Q_i , while it is not limited to this,

and a value in a certain fixed relation with the density of the pixel may be used. For instance, by supposing that the density is X , the value \sqrt{X} , $X^{1/a}$ may be used (where "a" is a constant").

5 A plurality of images to be recorded on the CGH 12 of the present invention as described above may be parallax images obtained by changing the direction of observation of a 3-dimensional object or of a changeable picture, which is turned to an entirely different picture when the direction
10 of observation is changed, or a series of animation images to be changed when the direction of observation is changed.

 Further, the divergent light emitted from the virtual point light source or the converging light converged at a virtual light converging point may be recorded on the plane
15 of the CGH 12 so that these light components may be superimposed on the divergent light from adjacent virtual point light source or on convergent light converged to adjacent virtual light converging point, or these may be recorded separately from each other and not superimposed on
20 each other. In other words, in the former case, when the spacing of arrangement of the virtual point light source or virtual light converging points is narrower than the width of the object wave from one point light source or from the light converging point spreading on the plane of CGH, the
25 number of the images to be recorded increases, and the resolution is also turned to be higher, while noise may be increased because interference fringes are superimposed on each other. With regard to angular division in x direction

and y direction of the luminance $A_{WLCi} (\theta_{xz}, \theta_{yz})$ and the
luminance $T_{WLCi} (\theta_{xz}, \theta_{yz})$, may be equal angle division or
angle division to have equal spacing on the plane of the
CGH 12 or may be the other division. In case the images
5 are recorded as superimposed on the plane of the CGH, if
the initial phase ϕ_{WLCi} is set to a constant value
regardless of the relation to each other, unevenness in the
reconstructed image is decreased, and this contributes to
the improvement of the quality of the images. In case the
1) images are not superimposed on the plane of the CGH, the
initial phase ϕ_{WLCi} may be set to a constant value so that
these are related to each other.

If the distance of the image from the plane of the CGH
is set to within 1 mm, more distinct image can be obtained,
15 and this is desirable.

Also, in the computer-generated hologram of the
present invention, it may be arranged in such manner that
the hologram of Fig. 1 and the hologram of Fig. 4 are
present and recorded in parallel to each other within the
20 hologram.

In the above, description has been given on the
computer-generated hologram of the present invention based
on its principle, while the invention is not limited to
these embodiments, and various changes and modifications
25 can be made.

INDUSTRIAL APPLICABILITY

As it is evident from the above description, according

to the computer-generated hologram of the present invention,
on a plane where a plurality of images are reconstructed
and which is separated from the plane of the hologram, a
multiple of virtual point light sources with luminance of
5 the positions of the images different depending on radial
direction or a multiple of virtual light converging points
with luminance equal to the luminance of the positions of
the images different depending on light converging
direction are defined. Light components radiated from
10 these virtual point light sources or light components
converged to these virtual light converging points are
regarded as virtual object light, and a computer-generated
hologram is prepared using these light components. The
present invention makes it possible to provide, for
15 instance, a computer-generated holographic stereogram with
high resolution and with many numbers of parallaxes.